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InAs/$Ga_{1-x}In_xSb$ Superlattices for Infrared Detector Applications

R. H. Miles

Hughes Research Laboratories
Malibu, California 90265

D. H. Chow and T. C. McGill

California Institute of Technology
Pasadena, California 91125

InAs/$Ga_{1-x}In_xSb$ superlattices have been proposed as possible alternatives to $Hg_{1-x}Cd_xTe$ for infrared detector applications, particularly in the $8-12\,\mu$m region and beyond.[1,2] Long wavelength response has been predicted based on the strongly misaligned (type-II) band alignment of the superlattice. Semimetallic behavior consistent with this band alignment has been demonstrated in InAs/GaSb superlattices ($\Delta E_v \simeq 510$meV), but only for comparatively thick layers ($\simeq 100$ Å).[3] As type-II structures confine electrons and holes in different layers, electron-hole overlap is poor for layers this thick, and as a consequence the optical absorption coefficients are small. It was proposed that long wavelength response could be achieved for substantially thinner layers by replacing the GaSb layers with $Ga_{1-x}In_xSb$, further misaligning the bands through strain effects and reducing the antimonide band gap.[1,2] Calculated absorption coefficients for these structures are comparable to those of $Hg_{1-x}Cd_xTe$.

We report the successful growth of InAs/$Ga_{1-x}In_xSb$ superlattices and their optical and structural characterization. Samples were grown by molecular beam epitaxy at fairly low substrate temperatures ($< 400\,^\circ$C). Structural quality was assessed by reflection high energy electron diffraction, transmission electron microscopy, and x-ray diffraction. Excellent structures were achieved for growth on thick, strain relaxed GaSb buffer layers on GaAs substrates, despite a residual threading dislocation density of $10^9\,\mathrm{cm}^{-2}$ originating at the GaSb/GaAs interface. Despite a lattice mismatch of 1.7%, InAs/$Ga_{0.75}In_{0.25}Sb$ superlattices are observed to be free of misfit dislocations at the thicknesses examined here, owing to the close lattice match between the superlattice and GaSb, which evenly distributes compressive and tensile stresses between the InAs and $Ga_{0.75}In_{0.25}Sb$ layers.

Photoluminescence and photoconductivity measurements indicate that the energy gaps of the strained-layer superlattices are smaller than those of InAs/GaSb superlattices with the same layer thicknesses, and are in agreement with the theoretical predictions of Smith and Mailhiot. Energy gaps of 80-250meV ($15-5\,\mu$m) have been measured for InAs/$Ga_{0.75}In_{0.25}Sb$ superlattices with $45-25$ Å/25 Å layer thicknesses. Our results demonstrate that far-infrared cutoff wavelengths are compatible with the thin superlattice layers required for strong optical absorption in type-II superlattices.

[1] D. L. Smith and C. Mailhiot, *J. Appl. Phys.* **62**, 2545 (1987).

[2] C. Mailhiot and D. L. Smith, *J. Vac. Sci. Technol. A* **7**, 445 (1989).

[3] G. A. Sai-Halasz, L. L. Chang, J.-M. Welter, C.-A. Chang, and L. Esaki, *Solid State Commun.* **27**, 935 (1978).

InAs/$Ga_{1-x}In_xSb$ SUPERLATTICES FOR INFRARED APPLICATIONS

R. H. Miles & J. N. Schulman, HRL
D. H. Chow & T. C. McGill, Caltech

OUTLINE

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- Motivation
- Growth & structural properties
  - TEM
  - x-ray diffraction
- Optical properties
  - photoconductivity
  - photoluminescence
  - absorption
- Conclusion, comparison with theory

InAs/$Ga_{1-x}In_x$Sb SUPERLATTICES

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- Proposed as IR detectors by D. L. Smith and C. Mailhiot (J. Appl. Phys. **62**, 2545 (1987)).
  - IR energy gaps tunable over entire spectrum
  - large absorption coefficients
  - favorable transport properties ($m^*_{e,\perp}/m_e \simeq 0.04$)
  - III-V processing

InAs/GaSb SUPERLATTICE ABSORPTION

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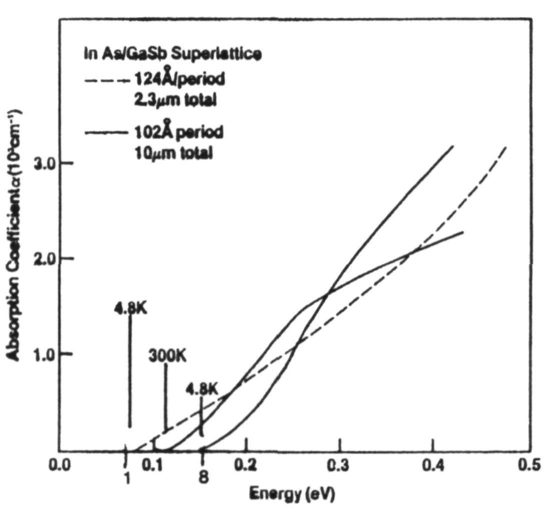
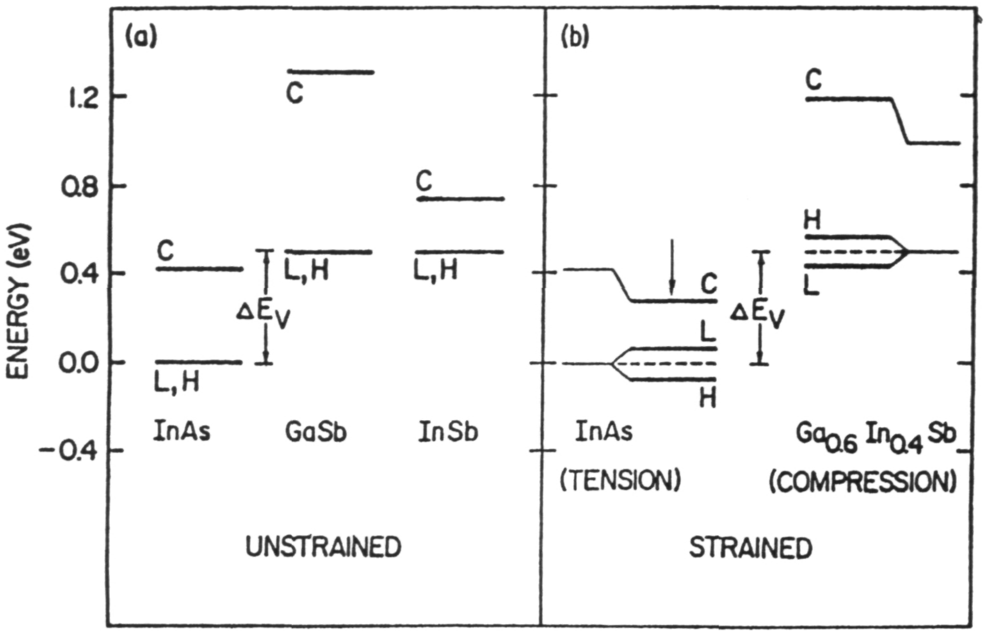
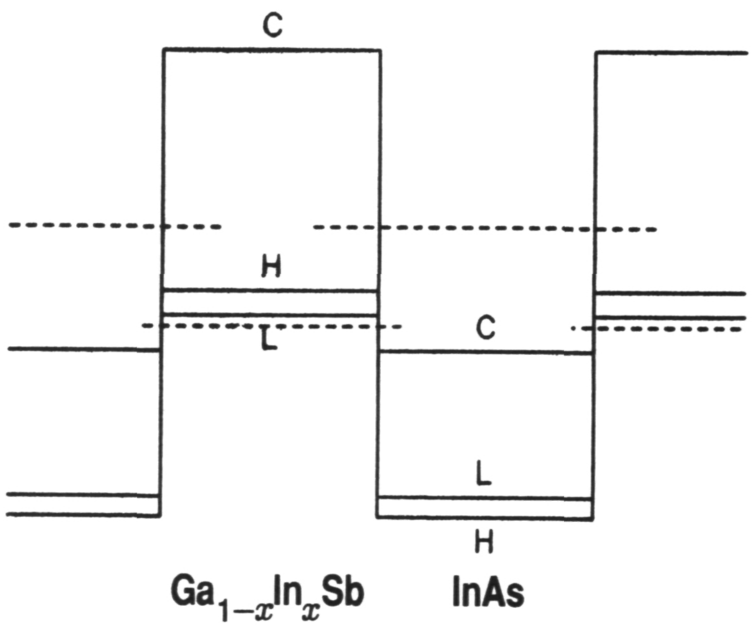


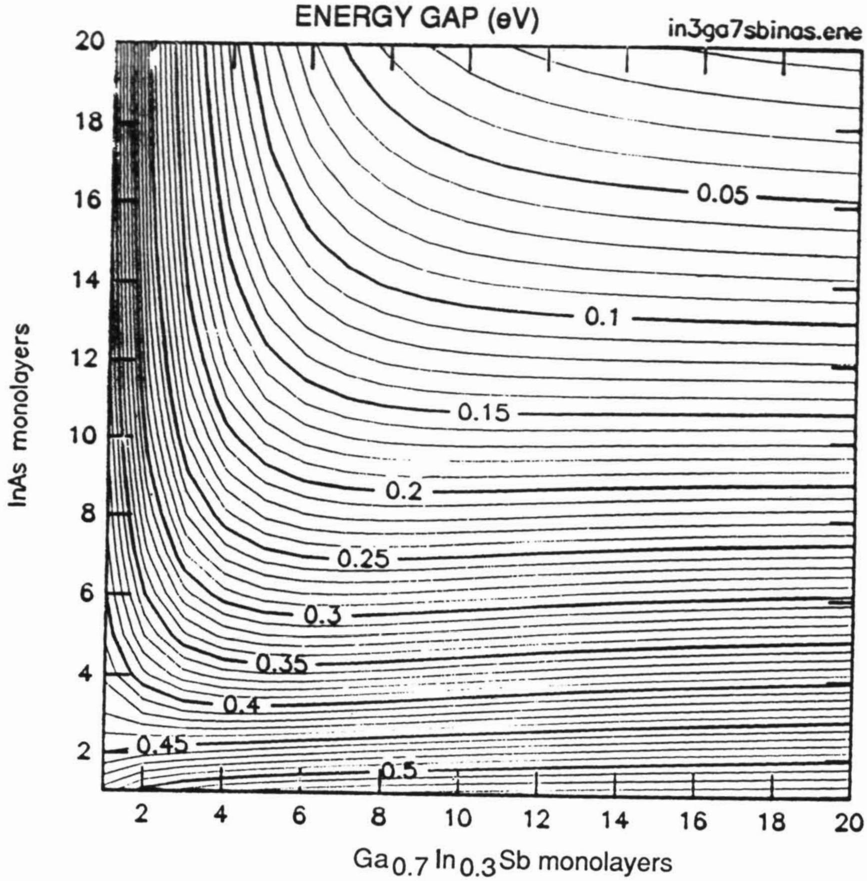
- D. K. Arch *et al., J. Appl. Phys.* **58**, 3934 (1985).

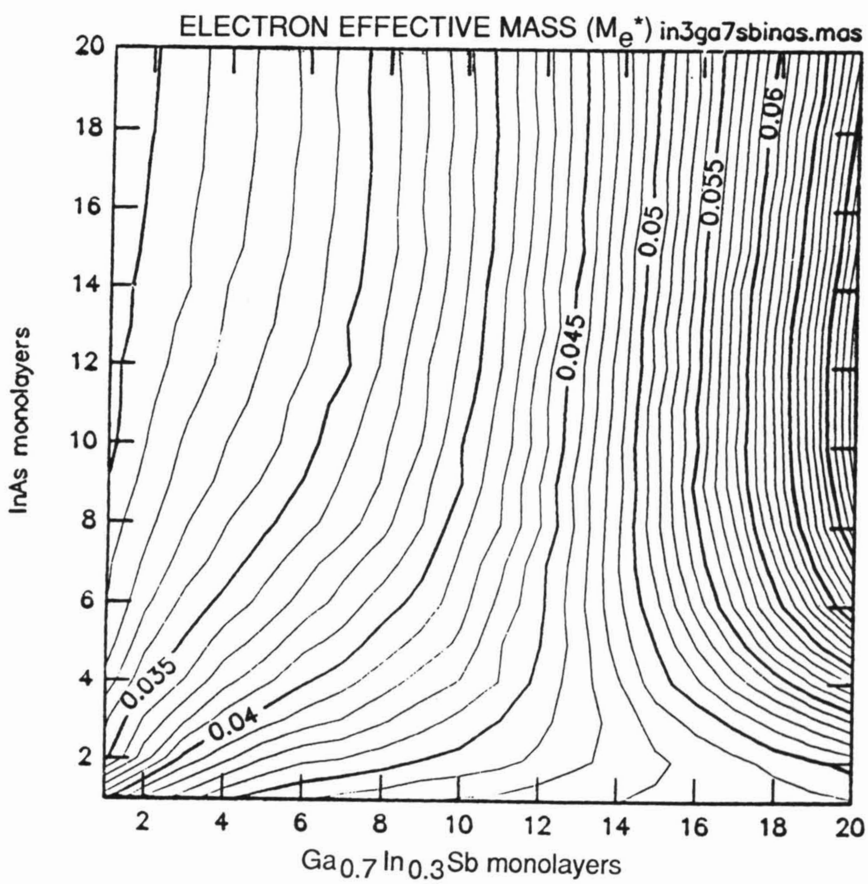


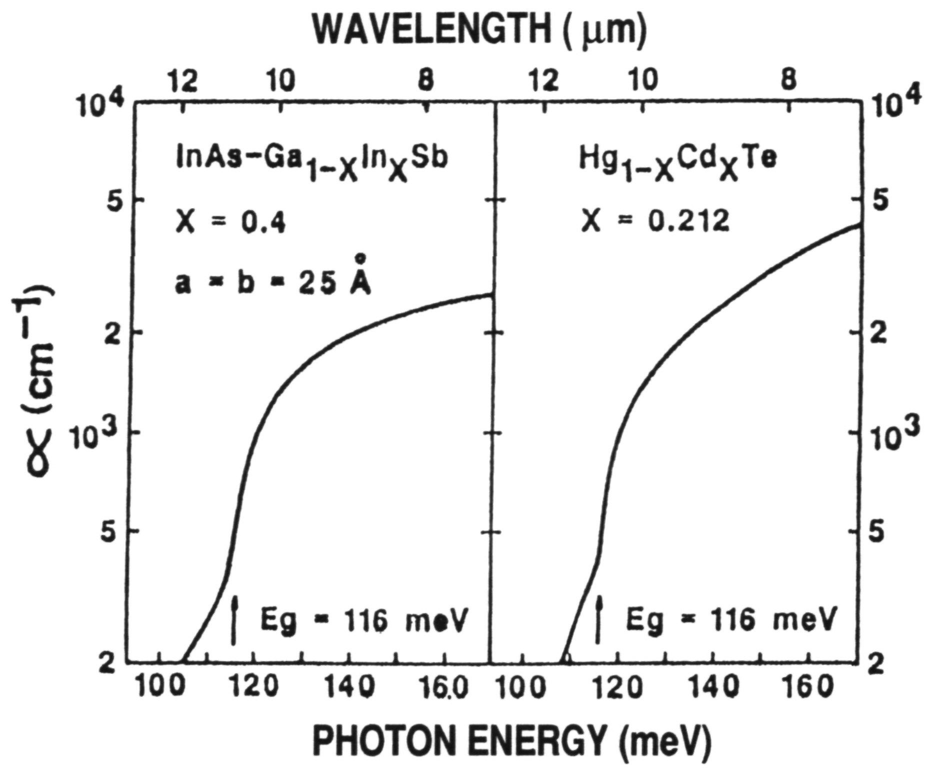
(Smith and Mailhiot)

InAs/$Ga_{1-x}In_xSb$ SUPERLATTICE BAND EDGES




ENERGY GAP (eV)
in3ga7sbinas.ene
InAs monolayers
$Ga_{0.7}In_{0.3}Sb$ monolayers
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5


ELECTRON EFFECTIVE MASS (M_e^*) in3ga7sbinas.mas
InAs monolayers
$Ga_{0.7}In_{0.3}Sb$ monolayers
0.035
0.04
0.045
0.05
0.055
0.06



InAs/Ga_{1-x} In_xSb Superlattices

Growth and Structural Characterization

A. Growth

- PHI 430 MBE system
- As_2 and Sb_2 (cracker) sources
- (100) GaAs substrates
- Substrate temperature monitoring

B. Structural Characterization Techniques

- Surface Morphology
- *in situ* Reflection High Energy Electron Diffraction (RHEED)
- X–ray diffraction
- Transmission Electron Microscopy (TEM)

As–incorporation in InGaSb Layers

I. Experimental

- Grew 2500 Å GaSb(As) Layer on InAs Buffer
- X–ray diffraction to determine As–incorporation

II. Growth Parameters Varied

- Substrate Temperature
- As background pressure
- Sb flux

III. Results

- Virtually no Sb incorporated in InAs layers
- Up to 30% As found in GaSb(As) layers
- Reduced As incorporation at lower substrate temperatures, reduced As background (< 7%)
- Sb flux has no effect on As incorporation in GaSb(As)

InAs/$Ga_{1-x}In_xSb$ Superlattice

Growth Conditions

I. Substrate Temperature

- Poor surface morphology, x–ray diffraction for $T > 400°C$
- Excellent surfaces, x–ray diffraction for 370 < $T < 400°C$

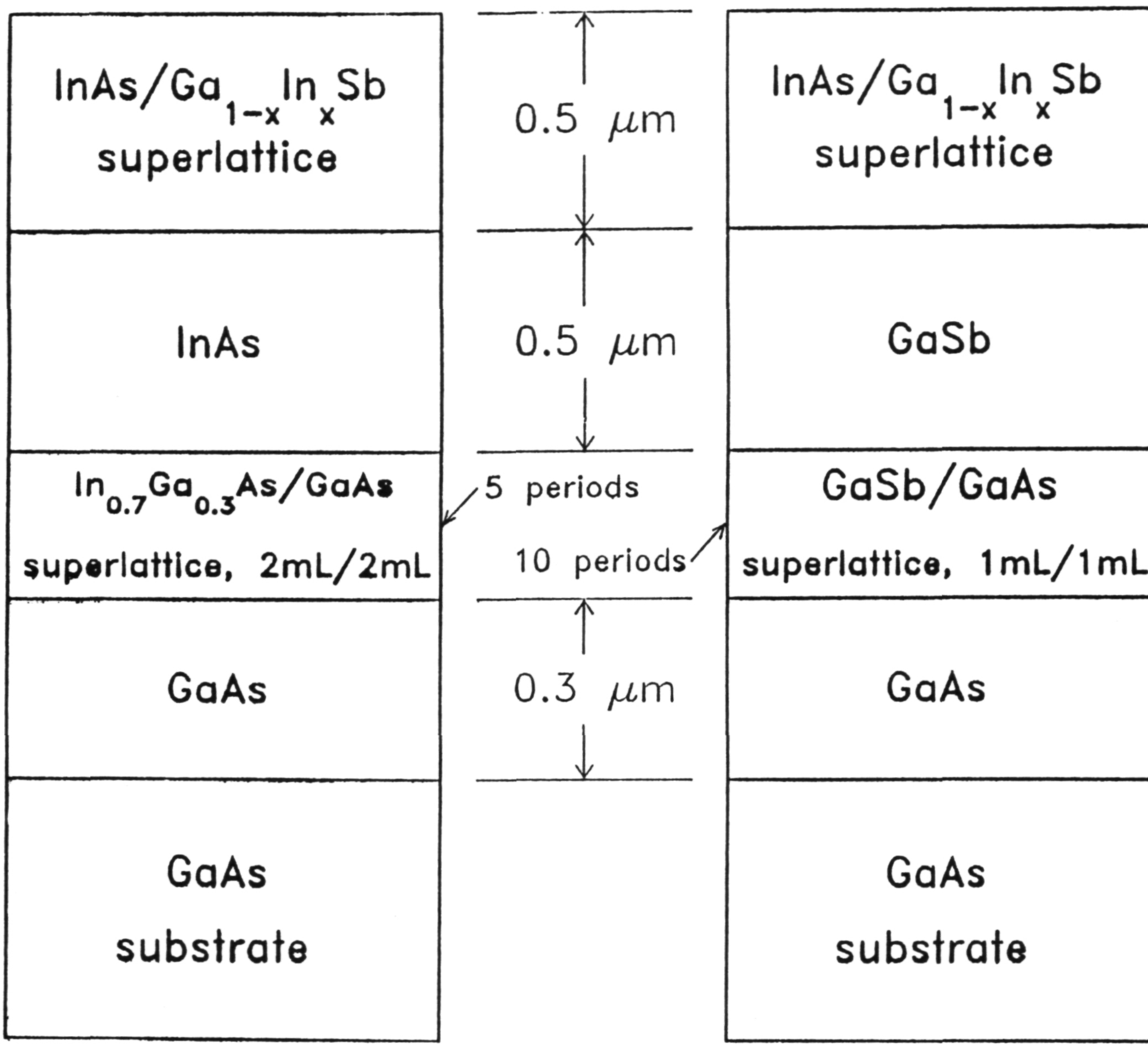
II. Growth Fluxes

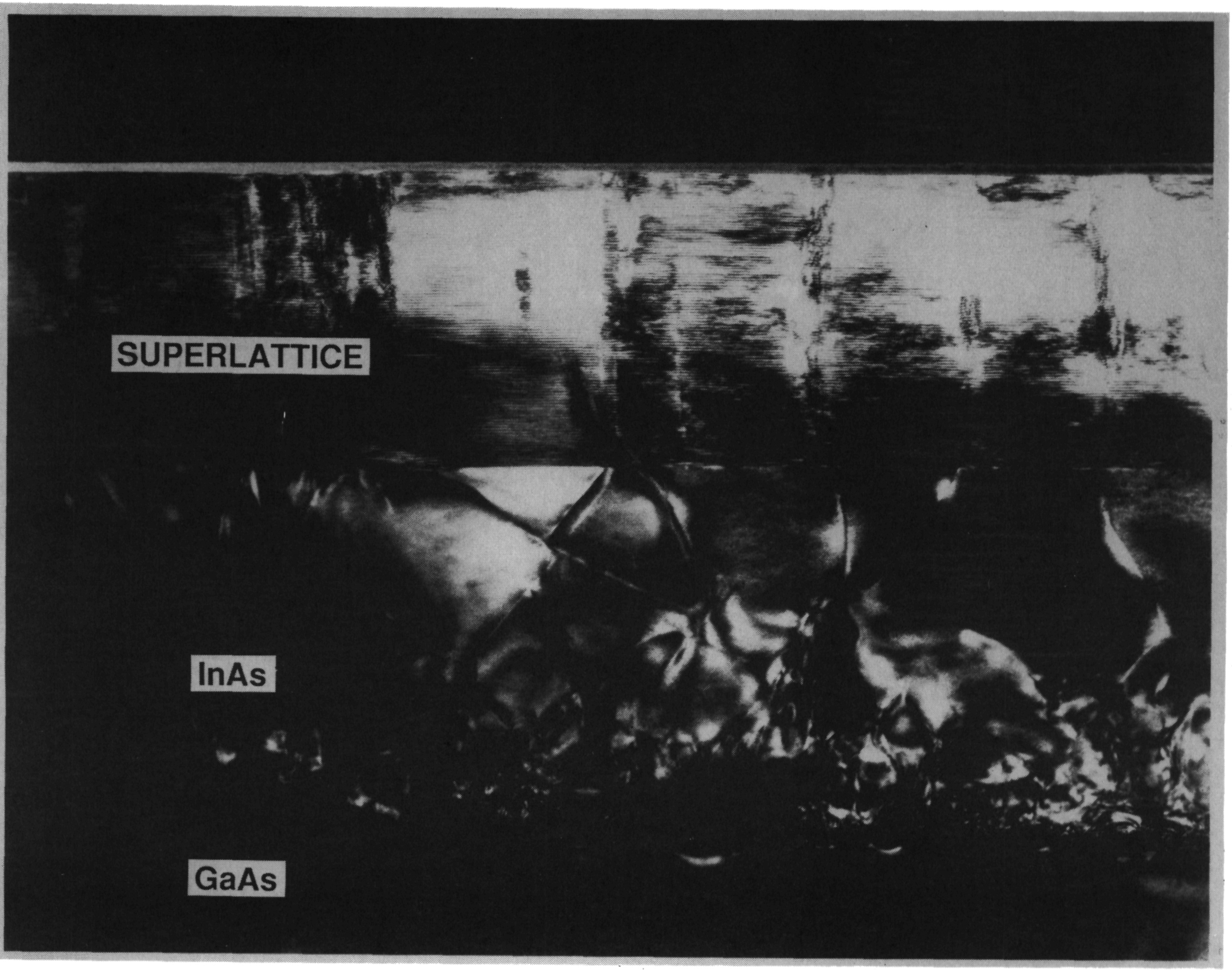
- InAs growth rate = 0.5 Å/sec
- $Ga_{1-x}In_xSb$ growth rate = 2.0 Å/sec
- Sb_2 flux >> As_2 flux

III. Surface Reconstruction

- 1×3 for $Ga_{1-x}In_xSb$
- 1×2 for InAs

SCHEMATIC LAYER DIAGRAM





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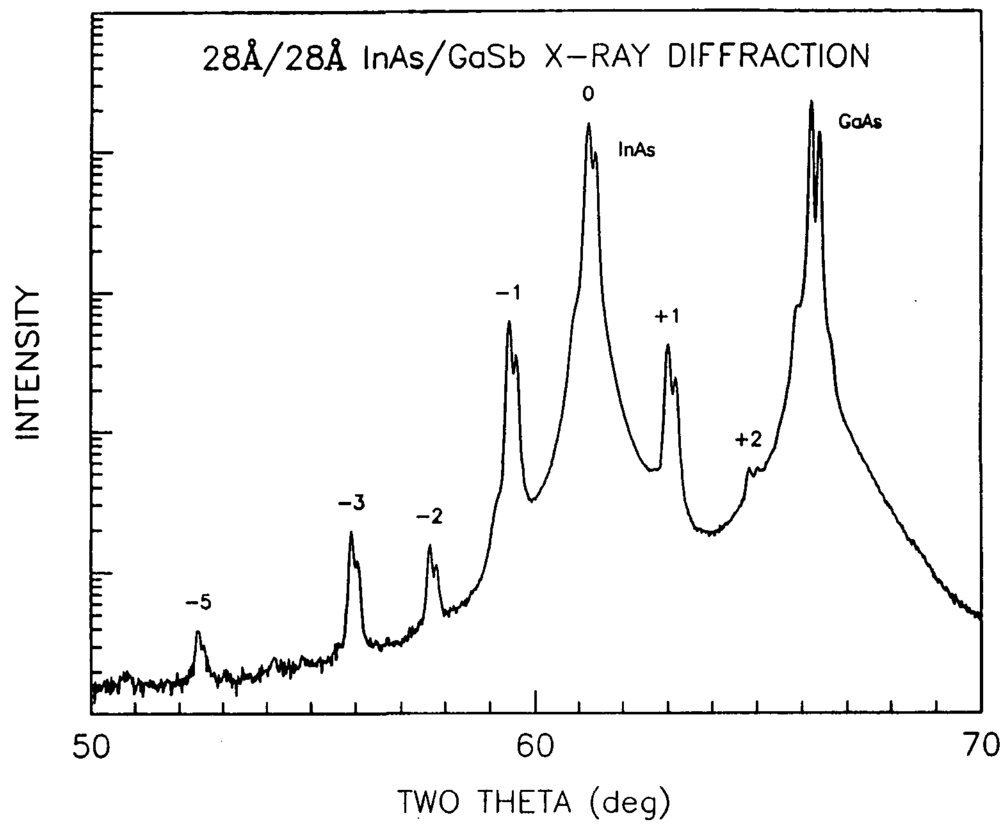
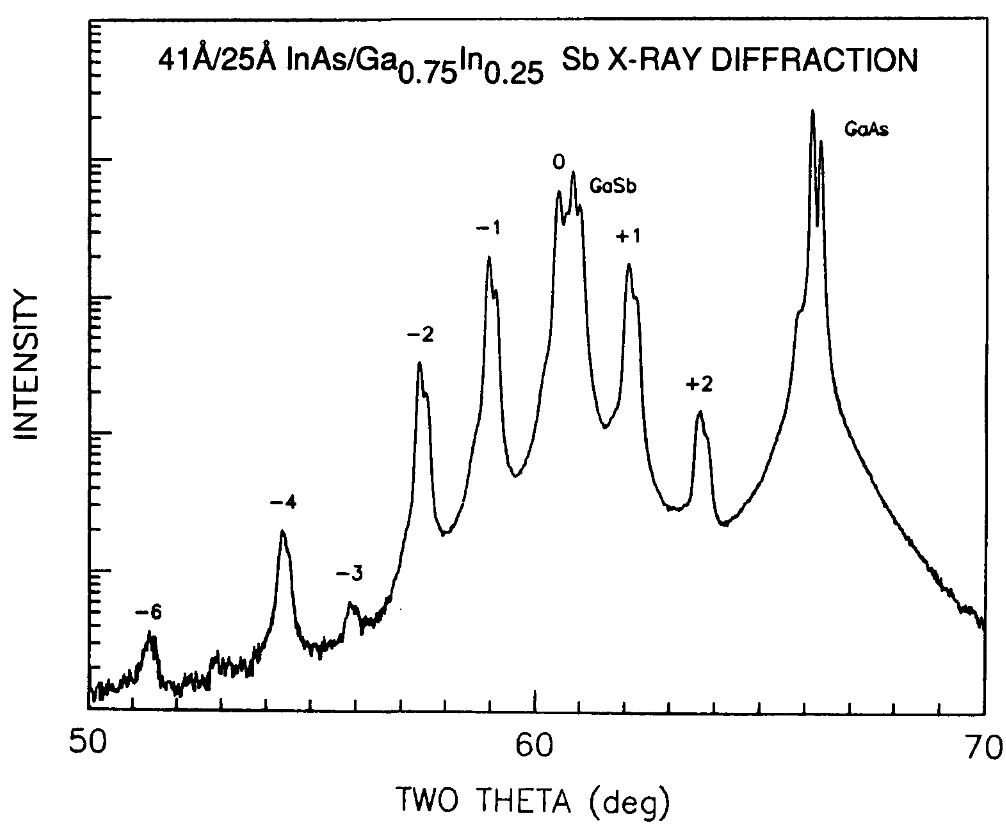

28Å/28Å InAs/GaSb X-RAY DIFFRACTION
0
InAs
GaAs
−1
+1
+2
−3
−2
−5
INTENSITY
50
60
70
TWO THETA (deg)


41Å/25Å InAs/Ga0.75In0.25 Sb X-RAY DIFFRACTION
GaAs
0
GaSb
−1
+1
−2
+2
−4
−3
−6
INTENSITY
50
60
70
TWO THETA (deg)

PHOTOLUMINESCENCE

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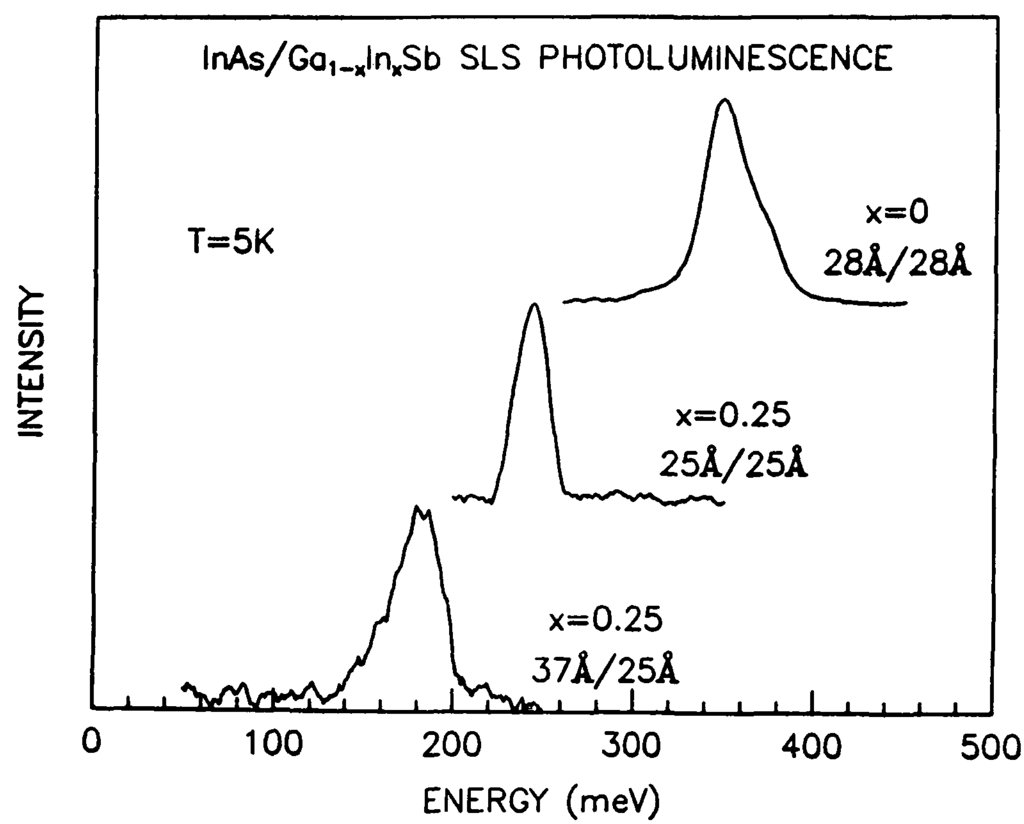
- OPTICAL EXCITATION
  - AlGaAs laser diode
  - Ar ion laser
  - 40 kHz modulation
- DETECTION OF LUMINESCENCE
  - Bomem Fourier Transform Infrared Spectrometer (FTIR)
  - lock-in amplifier
  - InSb or Si:As detector



PHOTOCONDUCTIVITY

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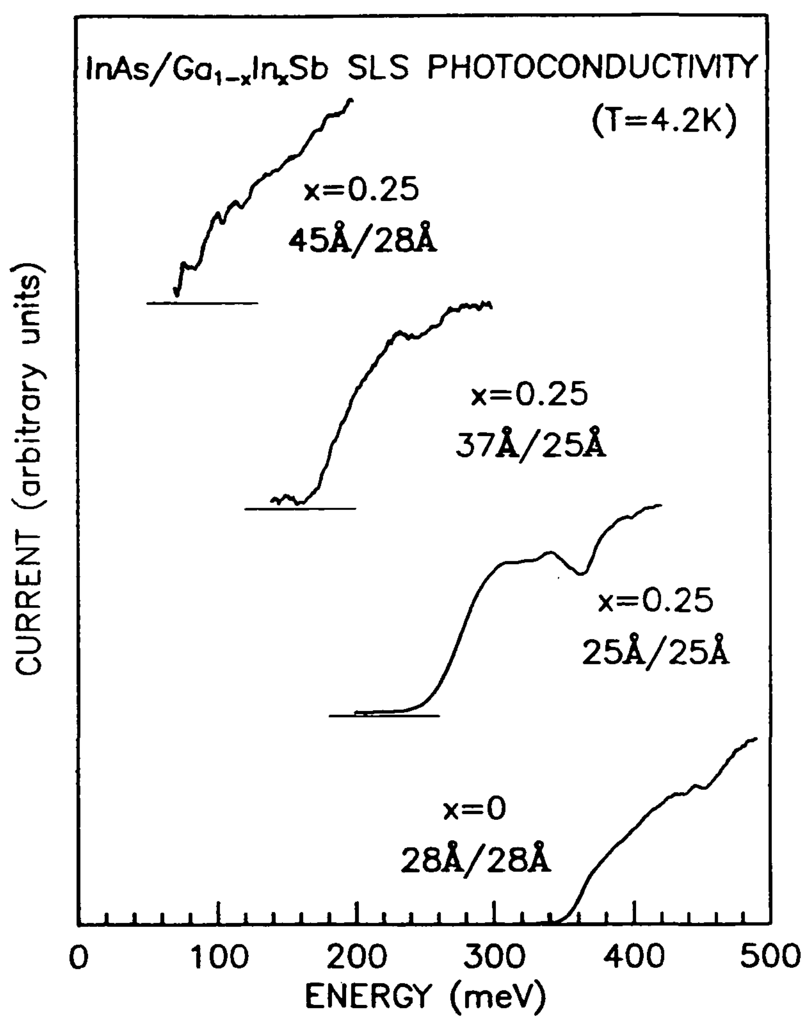
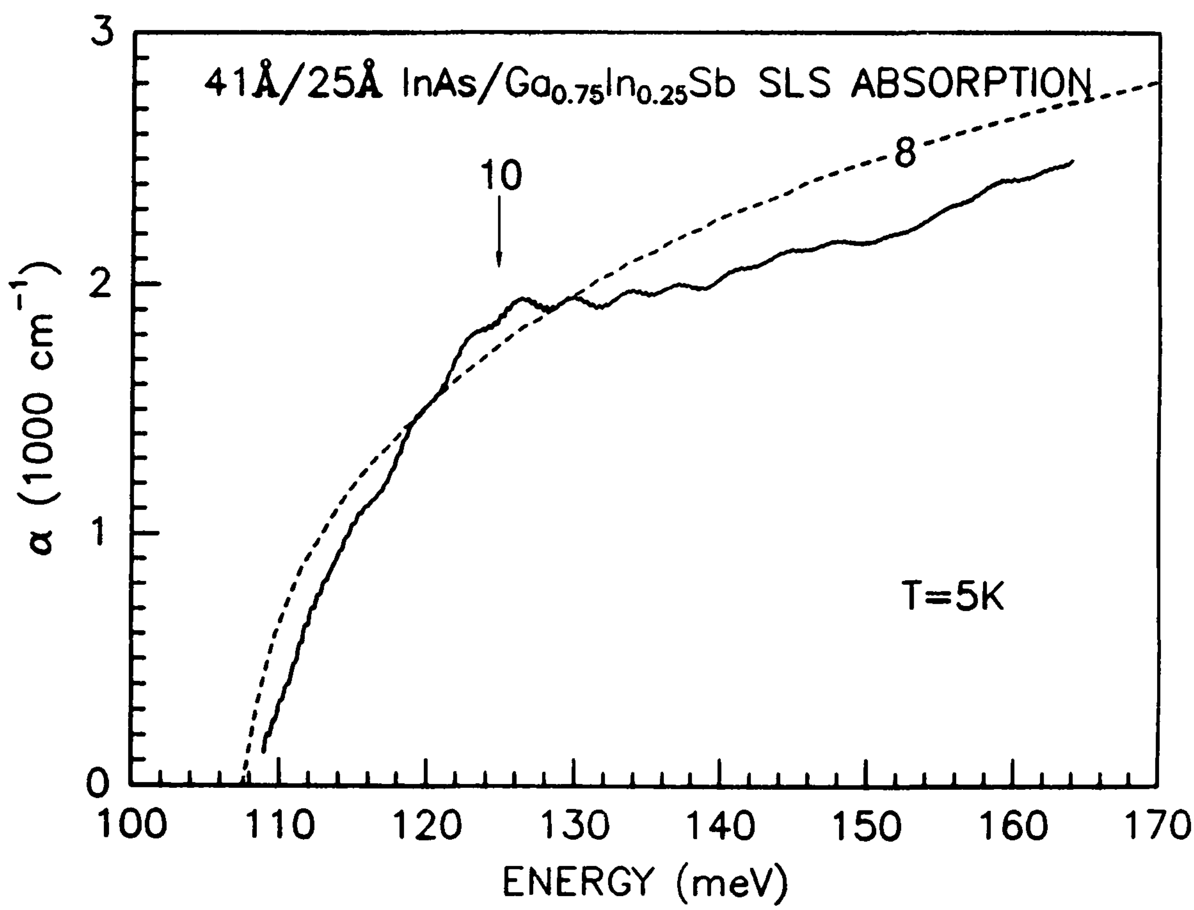
- SAMPLE PREPARATION
  - conventional photolithography
  - 60 x 160 μm mesas etched with Br_2:HBr:H_2O
  - Al contacts to mesas and etched surface
- MEASUREMENT
  - blackbody illumination from back (substrate) side of device
  - sample cooled over 5-300K range
  - sample used as detector in FTIR



LAYER THICKNESS (Å)				ENERGY GAP (meV)		
InAs	$Ga_{1-x}In_xSb_{1-y}As_y$	x	y	PL	PC	Theory
28	28	0	0.07	330±10	350±10	320
25	25	0.25	0.08	240±10	250±10	280
37	25	0.25	0.05	150±10	170±10	180
41	25	0.25	0	*	110±10	110
45	28	0.25	0	*	80±10	100

TABLE I. Comparison of energy band gaps derived from photoluminescence, photoconductivity, and theory for the InAs/$Ga_{1-x}In_xSb$ superlattices examined here.



InAs/$Ga_{1-\chi}In_\chi Sb$ SUPERLATTICES: CONCLUSIONS

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- GROWTH & STRUCTURAL PROPERTIES
  - GaAs substrates
  - $x = 0, 0.25, 0.35$
  - no misfit dislocations, $10^9 cm^{-2}$ threading dislocations
  - best structure for $370 < T < 400°C$
- OPTICAL CHARACTERIZATION
  - infrared photoluminescence observed
  - photoconductive response beyond 15 μm
  - energy gaps shift with strain as predicted
  - thin layers (¡75 Å period) yield far-infrared energy gaps
  - 10 μm absorption comparable to bulk $Hg_{1-x}Cd_xTe$